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EXAMPLES OF TIMBER STRUCTURE FAILURES

by Michael N. Salgo, M. ASCE

STRUCTURAL DIVISION

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EXAMPLES OF TIMBER STRUCTURE FAILURES

Michael N. Salgo,[1,2] M. ASCE

INTRODUCTION

During the accelerated construction program of World War II, wood construction experienced perhaps the greatest expansion in timber history. During this time timber framing systems using splitring, shearplate, etc., connectors, became widely used and modern timber construction came into its own.

The Bureau of Yards and Docks, in its construction program during World War II, designed and built timber structures for practically all types of Naval Shore Establishments. These included the well known "lighter-than-air" (LTA) hangars, glued laminated drill hall structures, floating drydocks, and hundreds of long span structures for varying uses, such as aircraft plants, shipyard shops, fabricating plants, etc. Hundreds of millions of dollars were expended in the construction and maintenance of long span timber structures by the Bureau of Yards and Docks in this program. It is of significance to note that relatively few major structural failures occurred with this tremendous construction program in spite of the pioneering nature of many of the designs. However, as over ten years have elapsed since the major portion was constructed, it is considered timely to review the records of this program and perhaps take advantage of the experience gained in these timber structures. The need has always existed and will continue to be necessary for correlation and integration of new designs with practical construction and maintenance requirements. Although there has been considerable literature available on laboratory test data for specific joint details such as connector details and specimen tests, there has been a conspicuous lack of actual design data correlating the results of tests and experiences with full scale construction.

The purpose of this paper is to present certain actual observed experience, particularly with reference to data on failures of timber structures observed over the past ten-year period. As stated above, the failures of known major timber structures have been relatively few, but failures did occur, and it is from these that certain lessons can be learned.

During the 1930's considerable research was underway on development of connector systems which could economically develop the high inherent tensile strength of lumber. A summary of much of this work was presented in the famous Forest Products Laboratory publication of Modern Connectors for Timber Construction.[3] Although the major portion and most spectacular of the long span timber structures were built during and subsequent to World War II,

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2. The opinions or assertions contained herein are the private one of the writer and are not to be construed as official or reflecting the views of the Navy Department or the Naval Establishment at large.
3. Modern Connectors for Timber Construction printed by U.S. Govt. Printing Office 1933.

there were a considerable number of unusual long span timber structures designed, built and standing long before this time, mostly in Europe. These earlier structures employed various systems of joint connections varying from Mill construction to the use of hard wood dowels and metal connectors much similar to our present day timber connector systems. The presently used system of splitrings, shearplates, etc., evolved from results of studies set forth in the Forest Products Laboratory publication[4] and has become the basis of most major timber construction to the present time. The system has proven itself. Timber structures using this system have proven to be economical and subject to standardization, mass production by prefabrication and erection methods similar to those used for steel structures. The availability and use of long span timber structures during World War II is considered to have been a major contribution to the war effort. It is of interest to note some typical examples of timber structures developed and built by the Navy's Bureau of Yards and Docks during World War II. Figure 1 illustrates a standard Building used in one of our Naval Shipyards.[5] These buildings are 100' x 250' with clear height of lower chord from floor varying for different buildings up to 25 feet. Buildings were prefabricated and subassembled over 1000 miles from site. Other interesting features were that chord members were glued laminated and that the largest size of individual truss members was 4" x 6". Fig. 2[5] illustrates a subassembly shop 79 x 550 ft. by 52 ft. high at the ridge. Building was designed for use in connection with Destroyer-Escort construction program. An entire "DE" could be built at one time in this building. 36 ft. wide by 30 ft. high doors were located in each bay to permit removal of the subassemblies. Building had two 5-ton bridge cranes. Figure 3 illustrates a standard Navy 200 x 600 ft. warehouse building. Structure has 200 foot span with two intermediate supports. This is same dimensions as steel and concrete standard Navy storage building. Figure 4 illustrates a multi-story shop building. The lower floor was used as a shipfitters shop whereas the second floor was used as a joiner shop. The lower floor had bridge cranes running on glued laminated crane runway girders. Figure 5[6] illustrates the Standard Navy Timber S.T.A. hangar. These hangars housed the blimps that played such an important part in the antisubmarine warfare effort during the early part of World War II. Hangar shell is 1000 feet long, 176 feet high at the crown with an overall width at ground level of about 296 feet. These structures are among the largest timber structures ever built.

Maintenance of Timber Structures

As the many Timber Structures were erected, the need for establishing inspection and maintenance standards for timber connector type trusses soon became evident. To this end the Bureau of Yards and Docks in October 1944 prepared a publication on "Maintenance Procedure for Timber Trussed Structures" (NavDocks P 106), part I of which was on maintenance procedures and part II on "Inspection, Maintenance and Repair of Timber Structures".

4. Modern Connectors for Timber Construction printed by U.S. Govt. Printing Office 1933.
5. Design and construction discussed in ENR article of 15 July 1943.
6. Design and construction of LTA Hangars discussed in some detail in October and November 1943 issues of Civil Engineering by Mr. A. Amirikian, Mem. Am. Soc. C.E. of the Bureau of Yards and Docks who was in immediate responsible charge of design of these hangars.

Similarly, "Timber Maintenance Methods" by Verne Ketchum in Western Construction News - January 1945 and "Are Timber Checks and Splits Serious" by Messrs. Ketchum, May and Hanrahan in Engineering News Record - July 27, 1944 - excellent articles, contributed greatly toward better inspection and maintenance of timber structures. Some of the reasons necessitating the specialized inspection and maintenance pertained to design, material, workmanship, and conditions inherent to the system of framing in timber connector type structures. Although most of the timber structures were designed by competent engineers, it was found that some structures were under-designed because of lack of design experience on behavior of wood construction and in a few cases because of lack of competent engineering services. In many cases, particularly the earlier war years, it was necessary under emergency conditions to use unseasoned and non-structural material or unseasoned material of a lower grade than specified. Much of the lumber used received its drying while in place as structural framing. There were many evidences of poor workmanship during World War II with timber structures. The volume of construction increased so rapidly that it was practically impossible to have sufficient artisans properly trained and skilled in this comparatively new field.

The author, as did many others in the field, had many occasions to note such malpractices as chiseling around split ring grooves to get a joint fit, inaccurate drilling of holes and grooves, omission of split rings (this made erection easier but was not very beneficial for the structural strength), cutting of grooves on both sides of members when only one side was required, cutting of shear-plate rings when split rings were to be used, etc. One case which, strange as it may seem, was observed by the author within the last year occurred where instead of using standard shear plates for a steel to wood connection sections of 4-inch pipe were being welded to the steel plate and fitted into grooves for 4-inch split rings. All of those deficiencies along with the problems in volumetric changes, flow in the wood and the use of data that did not anticipate these effects produced maintenance problems that were of appreciable significance. Results of improper maintenance manifests itself in many ways in wood construction. Failure to periodically tighten bolts may result in excessive vertical deflection, in bowing and twisting of members and in the split rings partially coming out of grooves with subsequent possible failure of the structure. One example of the latter will be discussed in some detail later in this paper. If checks or splits are not arrested progressive failure may occur.

The author's experience indicates that most failures in timber structures occur in individual truss members and do not result in the failure or collapse of the structure. There usually is an elastic and/or plastic readjustment among other framing members whereby the stresses are redistributed to other members in the truss assembly.

One of the factors causing most of failures in individual members noted occurred in unseasoned timbers where the slope of the grain was greater than the allowances for the lumber grade of the member. Such failures were observed in members of bracing systems and were particularly conspicuous when one timber of a double timber member failed and the remaining timber showed no sign of distress.

One if not the most important factor in timber connector type trusses is the bolt and connector details in joints of trusses with unseasoned timbers. The details should be arranged to minimize the effect of cross-grain shrinkage. The importance of this factor is illustrated by means of figure 6. Figure 6 illustrates the effect of differential shrinkage on timber connector type truss joints. Pertinent notes brought out by this figure follow:

a) Maximum stress conditions result from use of unseasoned timbers.
b) Parallel to grain shrinkage practically zero.
c) Parallel to grain strength of timber is high which practically "fixes" rings in position.
d) Perpendicular to grain shrinkage is relatively high.
e) Perpendicular to grain tensile strength of timber is weak.
f) As timber tends to shrink the "fixed rings" produce substantial cross grain tension stresses.

Experience with timber connector type structures and particularly parallel chord trusses, has been that deflections have been considerably in excess of that originally estimated from consideration of elastic strains. It has also been noted that the so-called "secondary stresses" resulting from elastic and plastic deformation of members and slip, plus stress deformation of ring connectors in many cases cannot be safely neglected. Figure 7 illustrates effects of large deformations. The joint detail, figure 7 (a) illustrated indicates wracking forces on the connectors that produce cross grain tension. The bending stresses in continuous chord members caused by deflection of the trusses is illustrated in figure 7 (b). The fibre stresses from this bending may at times exceed primary stresses. The complete analysis of complicated joints and so-called "secondary stresses" may become extremely difficult and at times impracticable. One approach to this problem would be to investigate the effect of typical joint motions, to adopt standards for joint details, minimizing the effects of these motions and to specify the use of reduced stresses for certain connector combinations. It has been noted that the "Specifications for Design of Structural Timber Framing" proposed for adoption by the American Institute of Timber Construction stresses the use of suitable standards for joints and connections in considerable detail.

Examples of Timber Structure Failures

LTA Hangars

Perhaps the most spectacular of the timber structures developed are the LTA Hangars. The Navy still has and is using many of these hangars on both east and west coast Naval Air Stations. The failure of the LTA Hangars at Richmond, Florida has already been adequately covered in previous reports. However, in connection with this failure, it is considered propitious to quote pertinent excerpts from the "Joint report on investigation of destruction during hurricane of the three LTA Hangars at the U.S. N.A.S. Richmond, Florida."

"Conclusions drawn from available evidence include: - - - - Under the circumstances it would be unreasonable to expect the structures as designed to withstand the loading imposed and, since it might be considered unreasonable and uneconomical to design structures of this character and magnitude to meet hurricane conditions to which these buildings were subjected, the collapse may be considered in the 'Act of God' classification."

This was an example where structures were properly designed, built and maintained, but failure resulted when winds of unprecedented magnitude hit the area. Structures were designed for 110 m.p.h. wind, whereas previous weather bureau records indicated a previous high of 87 m.p.h. (5-minute period) and an extreme velocity of 96 m.p.h. (fastest mile) for a 33-year period. Actual winds at time of failure were estimated to be at least 155 m.p.h. as a five-minute average, 170 m.p.h. as a 2-minute average, 178 m.p.h. for the fastest mile and extreme gust velocities to be as high as 250 m.p.h. - thus the "Act of God" classification. Attention is further invited to the fact that, exclusive of

the Richmond Hangars, the only factor used to determine whether the various L.T.A. hangars were to remain in use was pure military necessity.

Storehouse Building

A failure that can be attributed to design occurred in a standard storehouse structure (200 x 600 foot) at an inland supply depot. Figure 3 illustrated general framing of this structure. The two hundred foot span had two interior supports and it was at the interior supports that actual failure occurred. Details of the joint are shown in figure 8. The detail of the top chord connection provided for the opposing ends of the chords to be attached to opposite sides of the top of the wide timber column. This set up high cross grain tension stresses in the vertical members which caused splitting of the column and failure of the trusses. Figures 9, 10 and 11 further illustrate this failure in considerable detail. In Figure 9 the failure is at upper right of photograph. Temporary shores are in place at second and fourth panel point.

At the time of the failure it was decided to have a complete inspection made of timber structures on the Station. An engineering firm experienced in timber engineering accomplished this survey and inspection. Station personnel involved in maintenance of timber structures were assigned as observers and thus gained valuable experience. Revisions to the joint detail were made and remedial work was accomplished by Station forces. Structures are still functioning satisfactorily.

Shipyard Shop

As mentioned previously experience with parallel chord roof trusses has shown that actual deflections have been considerably in excess of predictions determined by use of published design data. As a result there have been a number of cases where serious consequences have ensued.

In one case in particular, this excessive deflection resulted in interference with operations of the bridge cranes in a shop. The question arose as to how to get the cranes back in operation. Maintenance personnel, obviously inexperienced and unfamiliar with timber structures, without consulting the engineering staff of the shipyard, found a quick, easy answer - cut off part of the ends of web members protruding below the bottom chord: This, of course, reduced the edge and end distance for all of the cut web members in the trusses but provided the extra few inches needed for bridge crane clearance for the time being only. However, the trusses continued to deflect and at this time fortunately the maintenance personnel referred the entire problem to the Engineering Staff. Further cutting of the end distances could have led to disastrous results. Various schemes were used to keep the bridge cranes in temporary operation, such as removing all second floor live loads - keeping the space unoccupied. A major rehabilitation design, using an ingenious system of steel rod auxiliary framing was prepared by the Shipyard Public Works Design Division. Structure has since been rehabilitated to permit its full use in accordance with original design loading.

Aircraft Plant

Early in World War II, considerable difficulties were being encountered with timber trusses at one of the aircraft plants under construction. Aircraft production in those days was of highest priority. Numerous failures were experienced and a report on conditions made by a firm of engineering consultants disclosed most interesting information. Two test trusses were set up using

actual trusses scheduled to go into the structure. Figure 14 shows the test set up.

These trusses were considered to be better than the average of those being used. One of the trusses had the bolts tightened, whereas the other had the bolts slackened off one turn (3/32-inches). The truss with tightened bolts carried over two-thirds more load than the truss with the slackened bolts. Figures 15 and 16 showing the test trusses indicate further some of the difficulties of the times with unseasoned and inferior material and construction and/or improper maintenance procedures.

Conclusions from this report indicated that failures were caused by the fact that bolt tightening operations were not accomplished, that inferior unseasoned material was used and no precautions were taken to use this material judiciously where effect of defects would be minimized. Following the investigation and report there were no further records of failures and unusual problems. Proper maintenance and more judicious use of materials was the answer.

Shipyard Multi-Story Shop Building

One of the most interesting failures from the structural engineers viewpoint concerns a shipyard multi-story shop building. Figure 4 illustrated general framing arrangement for this building. The lower floor was used as a shipfitters shop, whereas the upper floor held a joiner shop. One day in early 1949 under conditions of no roof live load, practically no wind load, and no floor live loads, an upper roof truss collapsed. The second floor of this building was only in intermittent use at that time. Figures 17 and 18 show actual typical conditions in the building noted after the failure.

Two separate investigations were made on the structural condition of this building - one by the Public Works Officer of the Shipyard and the other by a consulting engineering firm. The results were in general agreement and the more salient points are summarized as follows:

1) The timber trusses had in all probablility been built of unseasoned lumber and had not been properly maintained. Figures 17 and 18 clearly show the effect of shrinkage - bolts became loose and rings partially emerged from grooves.
2) An analysis was made of the original design, taking into consideration secondary stresses due to elastic, plastic and shrinkage strains and various conditions of joint restraint in addition to primary stresses. In some cases the so-called secondary stresses were computed to be as much as 300% of primary stresses. Figure 19 shows in tabular form representative results of the analysis for primary stresses.
3) Actual dead load of roof was considerably in excess of designed dead load. In addition, excessive deflections of the parallel chord roof truss caused a "hollow" in the roof where there was a permanent additional dead load of water. The total constant permanent load was actually in excess of the designed dead plus live load.
4) The design of the center splice was exceptionally weak. It was in this area that failure occurred. Figure 20 shows conditions at the splice typical of the trusses that had not failed. Note differential movement in individual chord members.

Figure 21 is a photograph of the truss that failed. Note the broken chord member and shifting at the splice.

This failure was actually caused by deficiencies in design, construction and maintenance. Everything went wrong. However, on the basis of the reanalysis

cited above, repairs and extensive maintenance is now being accomplished by lump sum contract. This building with an estimated present value of about $1,000,000 will be rehabilitated for less than $40,000! However, the allowable second floor live loads will be somewhat less than that contemplated by the original design.

SUMMARY AND CONCLUSIONS

There has been presented examples of failures in timber structures, the causes of which have varied from the "Act of God" category to deficiencies in design, construction and maintenance and combinations thereof. These have included some of the highlights of the author's experience with timber structures over the past fifteen years. A summary of conclusions based on this timber structure experience follows:

a) Many of the difficulties encountered in parallel chord roof trusses could have been eliminated or reduced by careful consideration of the bending stresses inherent in wood framed structures due to excessive deflections caused by slip and strain in the connectors. Avoidance of the bulk of the slip effects would have little effect on the construction costs and would encourage types of framing in which the slip would have reduced effect and thus achieve the optimum framing for timber structures. Design of timber structures (particularly long span parallel chord trusses) should, in addition to the usual analyses, include evaluation of secondary stresses resulting from movements of the connectors (slip and elastic deformation) and local stresses caused by eccentricities inherent in the framing system.

b) The effect of long duration loads on the plastic yield of wood should be given further consideration in establishing the allowable design stresses. This could be done by reducing the allowable stresses for higher ratios of dead to live load.

c) The timber bowstring truss, with or without timber connectors, has proven itself to be one of the most economical of roof framing structures from both the initial cost and maintenance viewpoints. Failures and maintenance problems with bowstring trusses have been practically non-existent in the author's experience.

d) If unseasoned lumber is to be used in trusses where the lumber will season in place, certain restrictions should be adhered to. One set of restrictions suggested for split chord or multiple chord trusses, other than bow string, provides that:
   1) no span shall exceed 75 feet
   2) the total length of unseasoned wood along the axis of a bolt for split ring connections shall not exceed 13-1/2". This dimension permits 5' 3" nominal size numbers.
   3) all trusses in excess of 50 feet in span shall have maintenance procedures recommended on design plans
   4) in truss joints with members in opposed grain arrangement connectors shall be limited to a two-bolt pattern

e) Particular care should be used when unseasoned timber is to be used in trusses subjected to rapid drying conditions, such as over ovens, boilers, or in dehumidified storehouses.

f) Maintenance and construction standards have been well established. There does exist an educational problem. There is need for more widespread knowledge of this information. Such articles as "Are Timber

Checks and Splits Serious", "Timber Maintenance Methods", are doing a great deal of good. These articles are designed for reading by engineers and artisans, who are actually building and maintaining timber structures. More such articles are needed.

g) Most of the difficulties experienced with timber structures can be attributed to incomplete designs, the use of unseasoned and lower grades of lumber, and lack of proper periodic bolt tightening operations. Timber structures properly designed, constructed and maintained have taken their place as major components in our present day construction program.

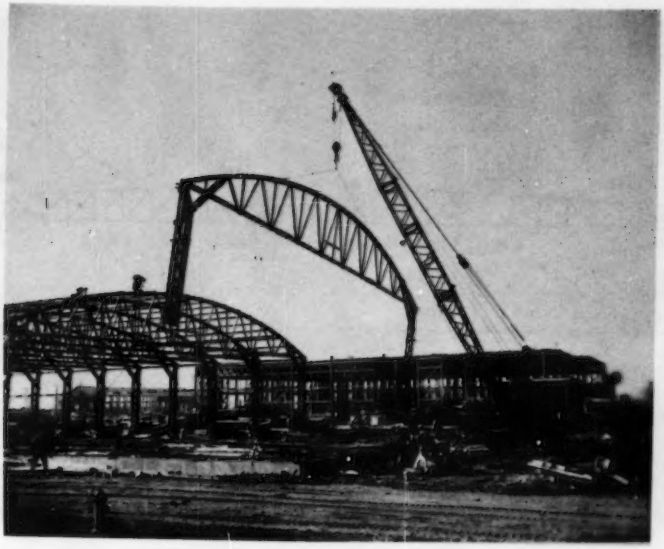


Figure 1 - A Standard Shipyard Shop Building

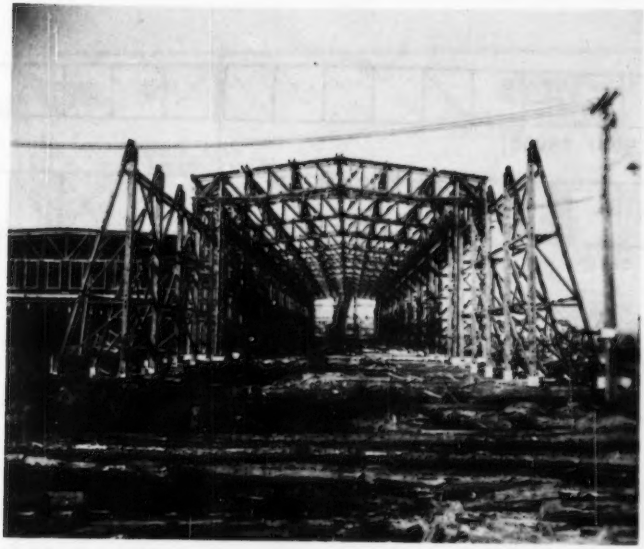
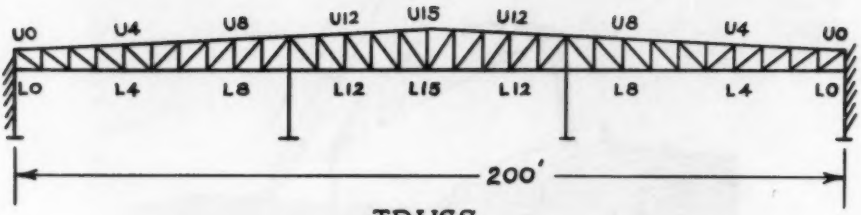
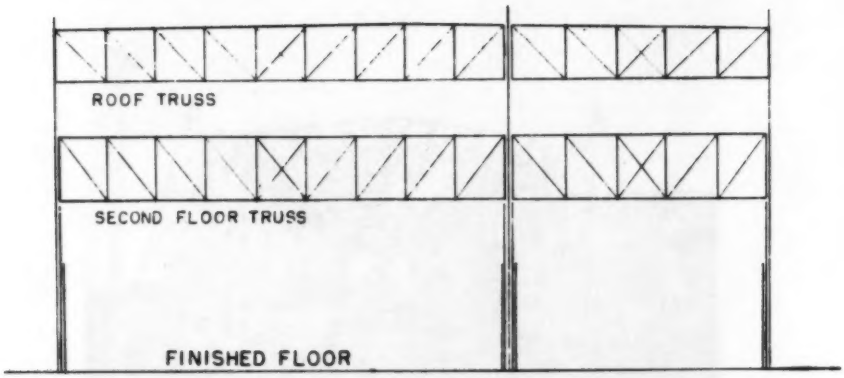


Figure 2 - Shipyard Sub-Assembly Shop



TRUSS

Figure 3 - Standard Navy Warehouse Building



SECTION A–A

Figure 4 - Shipyard Multi-Story Shop Building

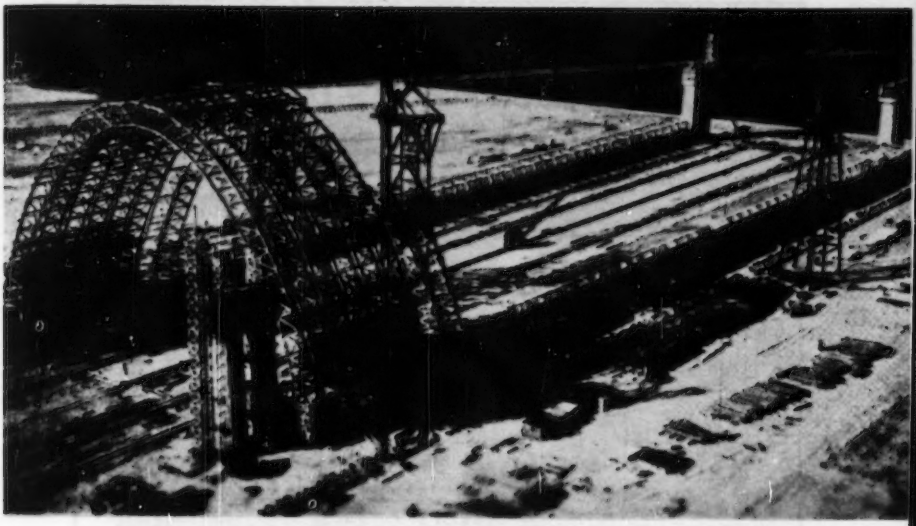


Figure 5 - Standard Navy LTA Hangars

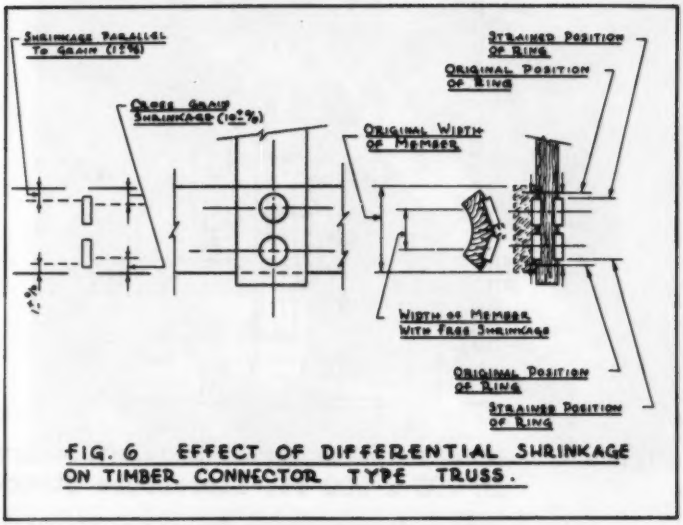
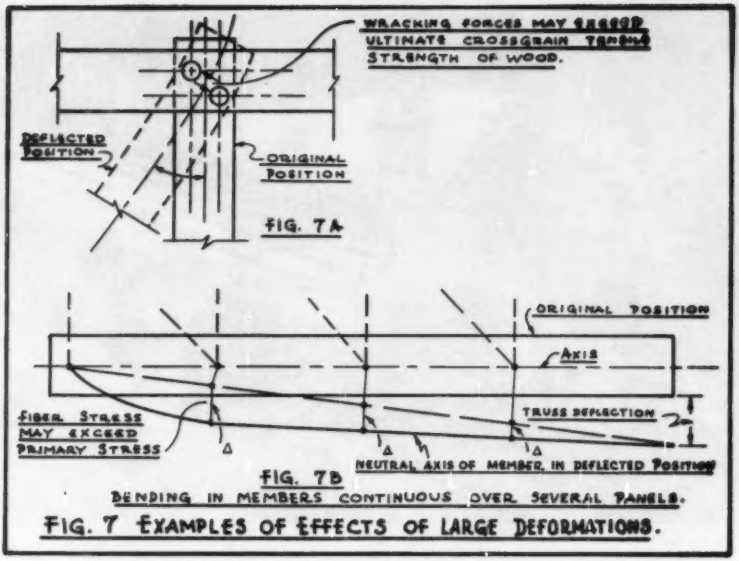

SHRINKAGE PARALLEL TO GRAIN (1%)
STRAINED POSITION OF RING
ORIGINAL POSITION OF RING
CROSS GRAIN SHRINKAGE (10%)
ORIGINAL WIDTH OF MEMBER
WIDTH OF MEMBER WITH CROSS SHRINKAGE
ORIGINAL POSITION OF RING
STRAINED POSITION OF RING

FIG. 6 EFFECT OF DIFFERENTIAL SHRINKAGE ON TIMBER CONNECTOR TYPE TRUSS.


RACKING FORCES MAY EXCEED ULTIMATE CROSSGRAIN TENSILE STRENGTH OF WOOD.
DEFLECTED POSITION
ORIGINAL POSITION
FIG. 7A
ORIGINAL POSITION
AXIS
FIBER STRESS MAY EXCEED PRIMARY STRESS
TRUSS DEFLECTION
NEUTRAL AXIS OF MEMBER IN DEFLECTED POSITION
FIG. 7B
BENDING IN MEMBERS CONTINUOUS OVER SEVERAL PANELS.
FIG. 7 EXAMPLES OF EFFECTS OF LARGE DEFORMATIONS.

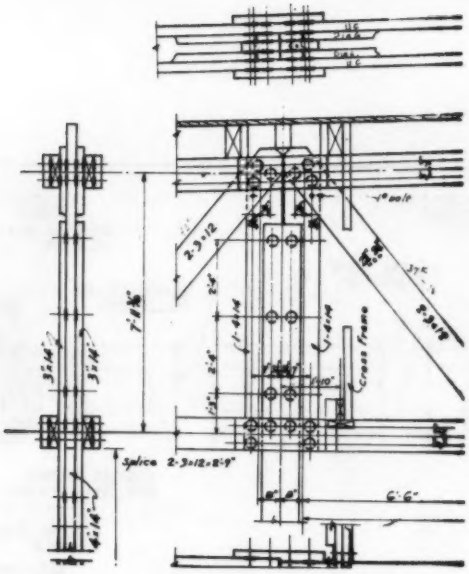


Figure 8 - Details of Interior Column Framing in 200 x 600 ft. Storehouse Structure.

Figure 9 - Failure in 200 x 600 ft. storehouse

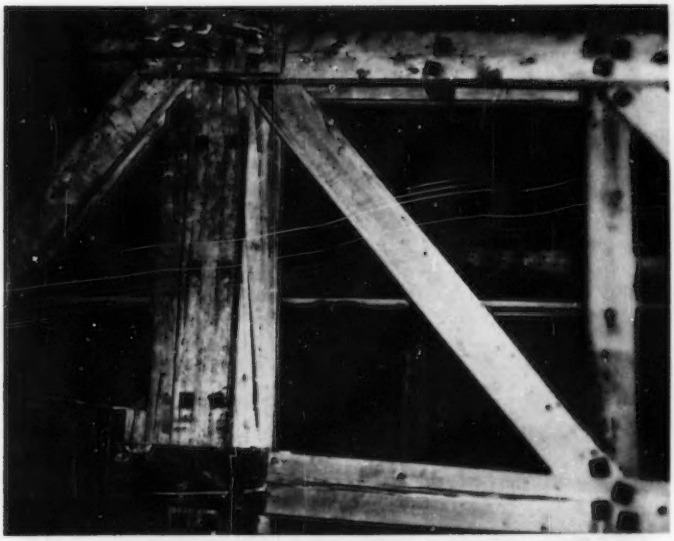


Figure 10 - Failure in 200 x 600 foot Storehouse

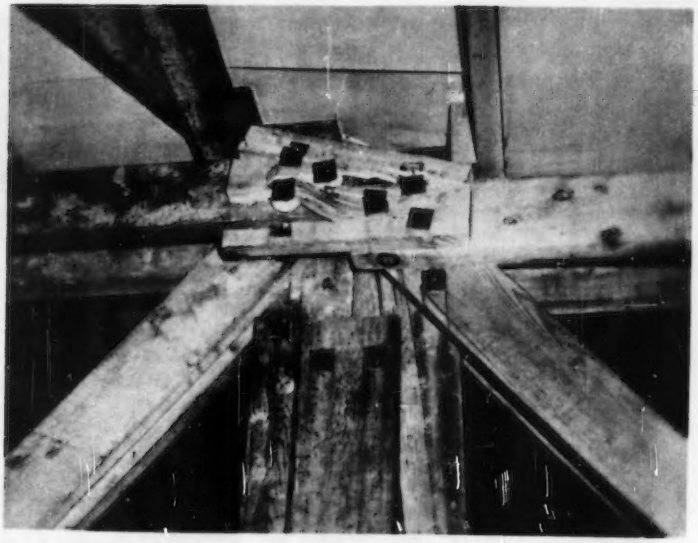


Figure 11 - Failure in 200 x 600 foot Storehouse

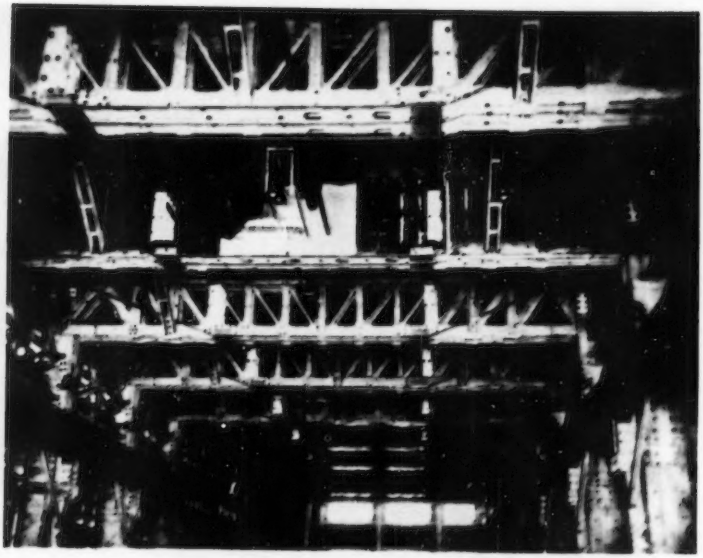


Figure 12 - Shipyard Boat Shop

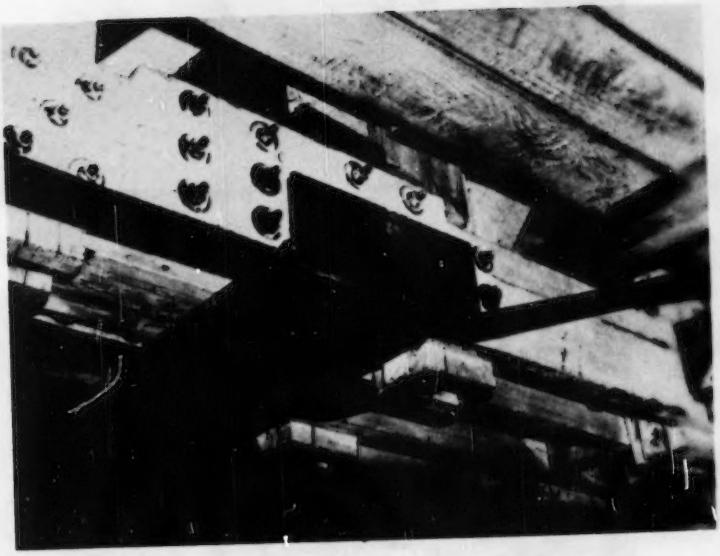


Figure 13 - Shipyard Boat Shop - Strengthening Details

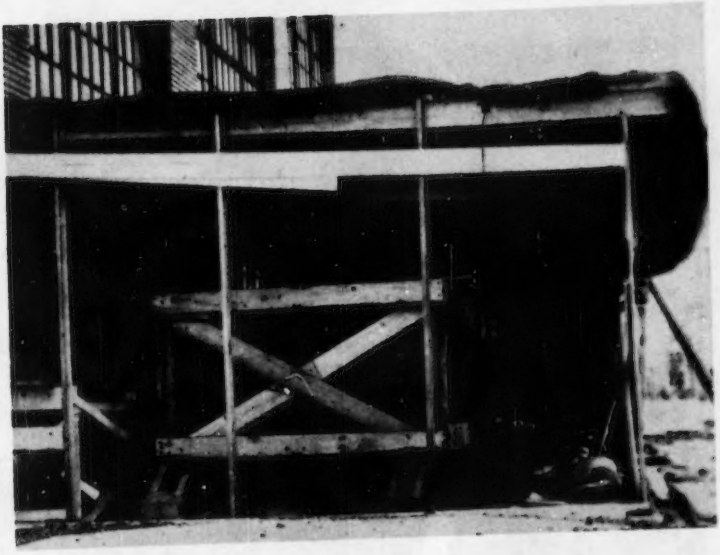


Figure 14 - Test Set Up for Two Trusses at Aircraft Plant

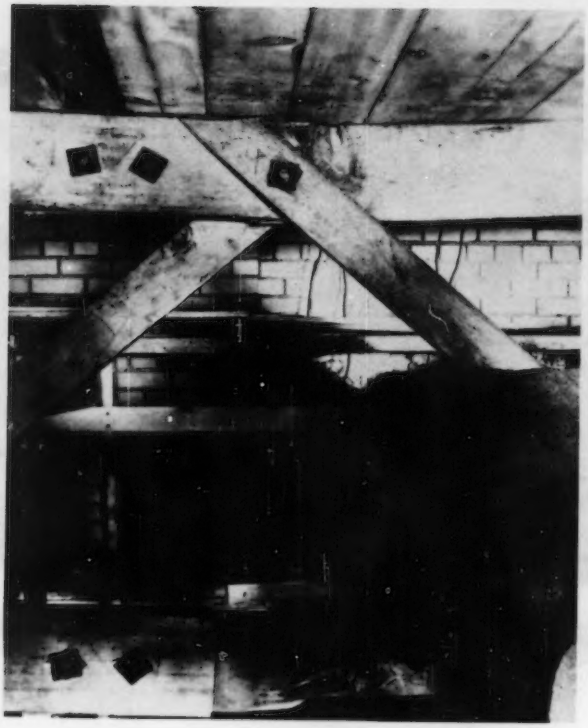


Figure 15 - Failure in Test Truss

Figure 16 - Failure in Test Truss

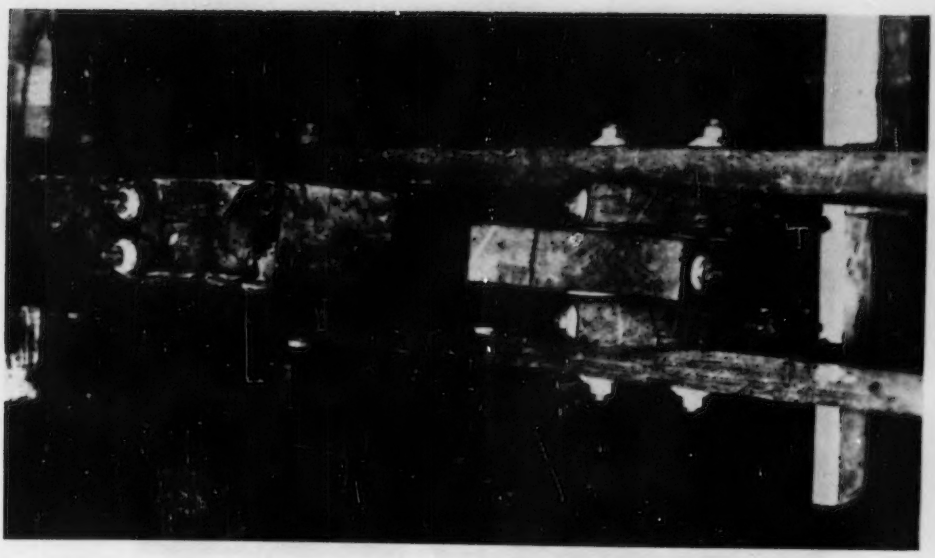


Figure 17 - Actual Framing Details in Multi-Story Shop Building

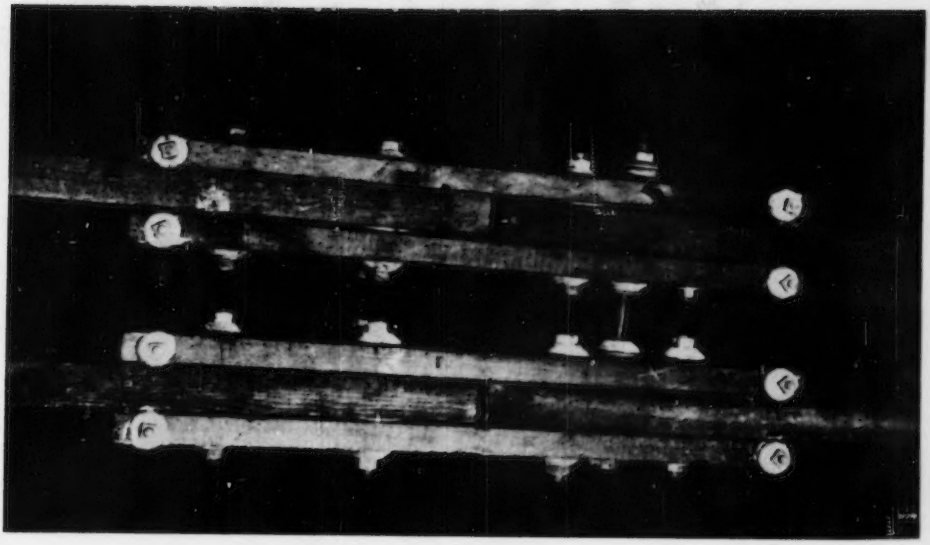


Figure 18 - Actual Framing Details in Multi-Story Shop Building

A ROOF TRUSS
DIRECT AND FLEXURAL STRESSES FOR ACTUAL LOADS DL = 58 psf LL = 40 psf.

Assumptions:
Web members and splices hinged.
Chord members continuous between splices.

Member	Direct Load Stresses Gross A	Net A	Flexural Stresses	Total Stresses Gross A	Net A
AB	350	420	348	698	768
BC	609	740		957	1088
CD	777	930	804	1581	1734
DE	863	1110	406	1269	1516
EF	850	1018	406	1256	1424
FG	843	1010	804	1647	1814
GH	758	983	345	1103	1328
HI	582	688	0	582	688
IJ	350	344	398	748	742
ab	0	0			
bc	556	725			
cd	963	1258			
de	1230	1600			
ef	1350	1940			
fg	1198	1560			
gh	423	1202			
hi	521	681			
ij	0	0			
Ab	702	916			
Bc	548	818			
Cd	388	572			
De	366	540			
Ef	32	53			
Fg	21	34			
Gf	292	450			
Hg	379	560			
Ih	580	793			
Ji	678	887			
Aa	830	1070			
Bb	724	816			
Cc	612	708			
Dd	472	548			
Ee	266	330			
Ff	235	278			
Gg	462	548			
Hh	510	577			
Ii	725	816			
Jj	830	1080			

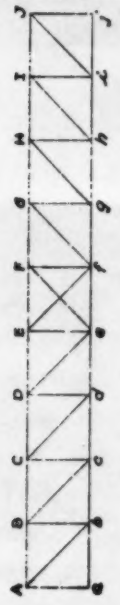


Figure 19 - Representative Results of Stress Analysis of Shipyard Trusses

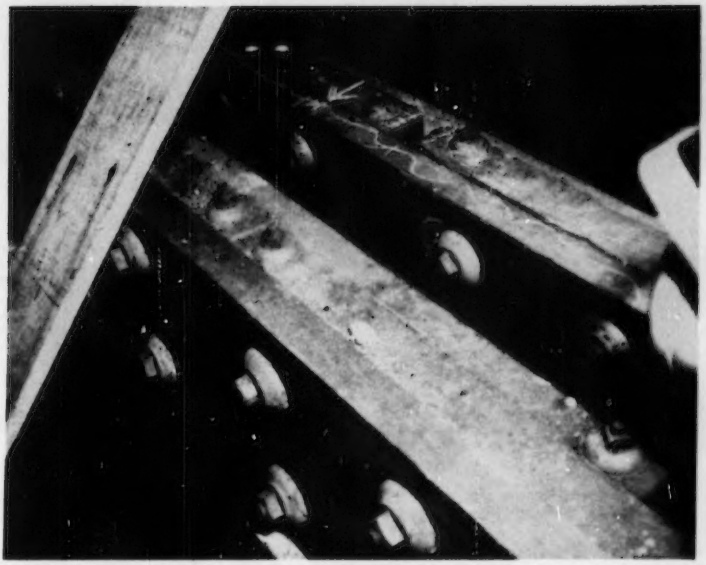


Figure 20 - Actual Framing Conditions in Multi-Story Shop Building

Figure 21 - Photograph of Truss that Failed

PROCEEDINGS-SEPARATES

The technical papers published in the past year are presented below. Technical-division sponsorship is indicated by an abbreviation at the end of each Separate Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering" or write for a cumulative price list.

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APRIL: 428(HY)[c], 429(EM)[c], 430(ST), 431(HY), 432(HY), 433(HY), 434(ST).

MAY: 435(SM), 436(CP)[c], 437(HY)[c], 438(HY), 439(HY), 440(ST), 441(ST), 442(SA), 443(SA).

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JULY: 457(AT), 458(AT), 459(AT)[c], 460(IR), 461(IR), 462(IR), 463(IR)[c], 464(PO), 465(PO)[c].

AUGUST: 466(HY), 467(HY), 468(ST), 469(ST), 470(ST), 471(SA), 472(SA), 473(SA), 474(SA), 475(SM), 476(SM), 477(SM), 478(SM)[c], 479(HY)[c], 480(ST)[c], 481(SA)[c], 482(HY), 483(HY).

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a. Presented at the New York (N.Y.) Convention of the Society in October, 1953.
c. Discussion of several papers, grouped by Divisions.
d. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.
e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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